

Materials Solutions for Converting Cast Iron Applications to Powder Metal

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ABSTRACT

In the last several years, powder metallurgy (P/M) materials have been developed to rival the properties of cast iron and screw machined grades utilized in both automotive and non-automotive applications. These materials offer the P/M industry a momentous opportunity to dramatically increase its market by replacing some of the cast iron volume utilized today. While the inherent net shape capabilities of P/M and the potential cost savings of conversion to P/M offer customers distinct advantages, previous materials have not offered property combinations comparable to many cast iron grades. This work will explore the common grades of cast iron and propose P/M materials as possible replacements for each.

INTRODUCTION

Ductile, or nodular, iron is a cast iron in which eutectic graphite separates from the molten metal during casting and grows as spheres instead of flakes [1]. The presence of such spheres imparts good tensile strength and ductility. Depending on the processing route chosen, ductile iron grades are capable of attaining ferritic, pearlitic, or martensitic microstructures.

Malleable iron is produced originally as a white cast iron and undergoes subsequent heat treating to form a ferritic, pearlitic, or martensitic structure. The heat treatment cycle for malleable cast irons consists of heating the white cast iron to ~925 °C up to 20 hours followed by rapid cooling to ~760 °C, then subsequent slow cooling to room temperature.

Given the vast array of possible microstructures, malleable and ductile irons can exhibit a varied range of mechanical properties. Tensile strengths have been known to range from 350 to 1000 MPa with corresponding elongation values of 20 to 2%. As with many other materials, ductile and malleable iron grades

traditionally lose ductility as higher tensile strengths are achieved.

The permutations possible in P/M rival those seen in cast iron grades. In addition to seemingly infinite compositional possibilities, P/M enjoys the net shape capabilities while avoiding the extensive environmental difficulties commonly associated with the castings industry. As shown in Figure 1, ferrous P/M parts achieve their often-exceptional mechanical properties by carefully coordinating three components – material composition, part density, and final microstructure [2]. Each of these factors can be carefully controlled in order to satisfy a wide assortment of stringent mechanical requirements.

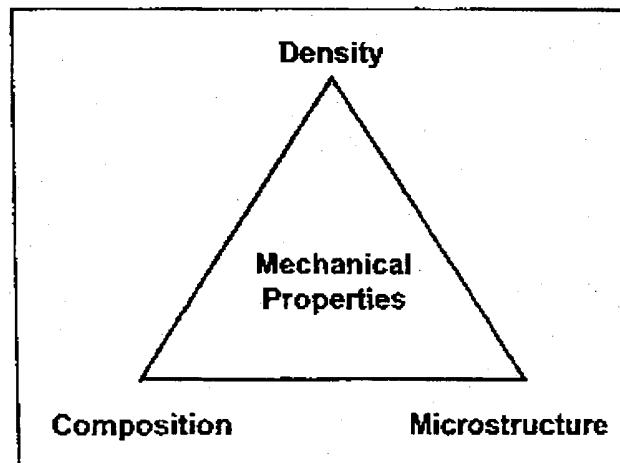


FIGURE 1: A Representation of the Factors That Determine the Mechanical Properties of Ferrous P/M Materials

In addition to the inherent challenges of converting cast irons to powder metallurgy grades, future design requirements from automotive manufacturers are slated

to become increasingly stringent. One of the most notable requirements is a 20% increase in power density, or torque per unit mass, for transmission gearbox components [3]. Not surprisingly, this performance mandate is expected to affect other automotive systems as well. Hence, the technological drive continues to identify powder metallurgy systems (materials and processes) capable of manufacturing complex parts while achieving high levels of mechanical performance, maintaining exceptional dimensional tolerances, and providing measurable economic benefits.

CONVERSION TO P/M

The successful conversion of cast iron to P/M invariably depends upon the P/M material employed, the process utilized, and perhaps, the manufacturing know-how and savvy of the P/M part manufacturer. However, material composition is most often the initial consideration – whether it is a proprietary in-house formulation or one available to the entire P/M community through a powder manufacturer. Hence, a compendium of powder grades and their prospective cast iron conversion targets seem of primary importance. Of secondary importance, but nonetheless required, are the P/M processes employed to facilitate the conversion.

CAST IRON GRADES – The tensile requirements for several common GM cast irons are presented in Table I [2,3]. The type of each cast iron and some additional grades are also listed. Some of the properties shown in Table I are easily achievable in common P/M grades, while the more stringent requirements require the use of P/M materials with higher alloy contents. However, the combination of strength, elongation, hardness, toughness, etc. seen in higher performance cast irons is often difficult to meet in conventional P/M compositions.

TABLE I: Key Specifications for Common Cast Irons

Cast Iron Grade	UTS (MPa / psi)	Yield (MPa / psi)	Elong. (in 2 in) %
GM 274M (gray iron)	125 / 18,000 Min	—	—
G 125 & G 250	250 / 36,000 Max	—	—
GM 84M (pearlitic malleable)	690 / 100,000 Min	550 / 80,000 Min	2 Min
GM 6129M (nodular)	400 / 58,000 Min ^a	260 / 38,000 Min ^a	15 Min
	690 / 100,000 Min ^b	550 / 80,000 Min ^b	2 Min

a = Grade 3815 (ferritic); b = Grade 8002 (martensitic)

P/M CANDIDATES FOR GRAY IRON – In general, the strength requirements to displace gray iron is quite low and therefore may only require P/M compositions containing iron and carbon, or perhaps, iron, copper, and

carbon. Some potential P/M alternatives for gray iron are listed in Table II along with their approximate density requirements [2,4]. While many other P/M compositions exist, only the most cost-effective materials are listed in Table II. The densities and resultant properties of the P/M alternatives are achievable by conventional pressing and sintering without the need for enhanced processing through warm compaction and/or high temperature sintering.

TABLE II: Potential P/M Alternatives for Gray Iron

Gray Iron Grade	P/M Alternative	Approximate P/M Density (g/cm ³)	Comments
G 125	F-0005	6.60	Meets Strength; Lowest Cost
	FC-0200	6.60	Meets Strength
	FC-0205	6.70	Meets Strength and Hardness
G 250	FC-0206	6.30	Meets Strength
	FC-0208	6.70	Meets Strength and Hardness

P/M CANDIDATES FOR FERRITIC NODULAR IRON – The conversion of ferritic nodular grades to P/M can be a particularly daunting task because of high ductility requirements. If a minimum elongation of 15% is absolutely required in an application, it is unlikely that conventionally pressed and sintered P/M would be capable of replacing the casting. Powder forging may offer an alternative, but this topic is beyond the scope of this review. However, specific applications certainly exist that require lower ductility levels. In these cases, P/M may be competitive with castings. Some of the P/M candidates for such an undertaking are listed in Table III.

In addition to relatively high ductilities and good strength, the phosphorous-containing materials exhibit good magnetic properties. As listed in Table IV, the higher phosphorous material also exhibited acceptable apparent hardness values and may be useful in applications requiring wear resistance such as the electromechanical components of interactive torque management (ITM) systems [5]. However, higher phosphorous contents can lead to lower impact toughness values and should be considered carefully if impact toughness is an application requirement. As seen in Table IV, higher temperature sintering is capable of increasing the performance of the phosphorous materials and can be employed if conventional sintering does not meet an application's mechanical property requirements. Copper is often utilized in conjunction with

phosphorous in applications such as main bearing caps in order to remediate the shrinkage common with phosphorous additions.

TABLE III: Potential P/M Alternative for Nodular Iron

P/M Alternative	Approximate P/M Density (g/cm ³)	Comments
FL-4400 + 5.5 w/o Fe ₃ P	7.10 – 7.30	--
FL-4400 + 3 w/o Fe ₃ P	7.10	Low Hardness*
FC-0205	7.10	Low Elongation*
FC-0208	6.70	Low Elongation*
FN-0208	7.10	Low Elongation*
FN-0405	7.00	Low Elongation*

* May be acceptable; Depends on application

TABLE IV: Properties of Phosphorous-Containing P/M Materials Sintered in 75 v/o H₂ [6]

Material	Density (g/cm ³)	Tensile (MPa / psi)	Elong. (%)	Hard. (HRB)
FL-4400 + 5.5 w/o Fe ₃ P	7.29	450 / 65,000	8	75
	7.28	500 / 73,000	12.5	77
FL-4400 + 3 w/o Fe ₃ P	7.14	430 / 62,000	7	68
3815 Ferritic Nodular	—	400 / 58,000 Min	15	75-90

BOLD data for specimens sintered at 1260 °C; all other specimens sintered at 1120 °C

P/M CANDIDATES FOR PEARLITIC MALLEABLE AND MARTENSITIC NODULAR IRONS — P/M part manufacturers have long been searching for materials and processing routes capable of producing pressed and sintered parts that meet or exceed the properties of pearlitic malleable and martensitic nodular cast irons. Although strength, ductility, toughness, or apparent hardness specifications can often be achieved

separately, it has been relatively difficult to meet all targets simultaneously for more demanding applications. For instance, previous work has shown that a warm compacted FLN4-4405 material sintered at 1260 °C meets the ultimate strength of a heat treated malleable cast iron (900 MPa), and almost meets the yield strength (690 MPa) but falls short of the 4% elongation of the cast iron [6,7]. When sintered at 1120 °C, the FLN4-4405 material exceeds the strength of the pearlitic malleable iron but has much less ductility (2.5% compared with 8%).

Arguably, the greatest collection of P/M compositions for the replacement of pearlitic malleable / martensitic nodular cast irons are found under the designation Ancorloy®. This trade name identifies a series of high performance, binder-treated premixes whose elemental constituents may include carbon, copper, molybdenum, nickel, and/or silicon. The entire series of materials and their respective compositions are listed in Table V. This series is capable of achieving ultimate tensile strengths ranging from 525 MPa to 1250 MPa (75,000 to 180,000 psi) and elongations ranging from 1% to almost 4%. While grades 2, 4, DH-1, and HP-1 are binder-treated analogs of diffusion-alloyed grades listed in MPIF Standard 35 [4,8], grades MDA, MDB, and MDC are materials specifically engineered to replace select malleable and ductile cast irons.

TABLE V: Nominal Chemical Compositions of High Performance, Binder-Treated P/M Materials

Grade	C (w/o)	Cr (w/o)	Mn (w/o)	Ni (w/o)	Si (w/o)
MDA*	0.90	—	—	—	0.70
MDB*	0.60	—	0.85	2.0	0.70
MDC*	0.60	—	0.85	4.0	0.70
2	0.60*	1.50	0.50	1.75	—
4	0.60*	1.50	0.50	4.00	—
DH-1	0.60*	2.00	1.50	—	—
HP-1	0.60*	1.75	1.50	4.0	—

* Specifically developed to replace cast irons

* Carbon content can be varied

All grades effectively cover a range of properties around those required for pearlitic malleable and/or martensitic nodular iron. If any difficulty exists in attaining the properties shown in Table I, it would certainly involve meeting the minimum tensile elongation of 2%. A conscious effort must be made to balance strength and ductility by prudently selecting carbon content and sintering parameters. In all but silicon-containing materials, processing conditions resulting in a microstructure of 100% martensite generally lead to elongations at or below 1%. However, by employing

silicon-containing materials and/or carefully tailoring sintering parameters and carbon content, higher elongation values are possible.

The mechanical properties of materials 2, 4, DH-1, and HP-1 are achieved by sintering at 1120 °C and subsequently tempering at 190 °C to relieve stresses resulting from the precipitation of low temperature transformation products during cooling from the sintering temperature [8]. Table VI contains the performance data for these grades. High temperature sintering and ANCORDENSE® processing (warm compaction) may be employed in order to increase properties, but are not required for the processing of these materials and are therefore ignored in this effort.

On the other hand, the silicon-containing materials, MDA, MDB, and MDC, require sintering at or above 1260 °C to realize the full benefit of the 0.70 w/o silicon content. The addition of a tempering step generally ensures the highest possible performance in any particular production environment. Given these guidelines, all data presented in Table VII are limited to these processing parameters. Once again, warm compaction may be employed in order to increase density and performance, but are not necessary to produce parts from these materials. In addition to meeting the minimum mechanical property specifications for martensitic nodular grade 8002, MDC consists of 90+ % martensite and exhibits apparent hardnesses of 26 - 40 HRC.

Depending on specific application requirements, a number of the P/M materials listed can perform similarly to a pearlitic malleable or nodular martensitic cast iron. Figure 2 graphically depicts the strength and elongation requirements of GM 84M and provides some insight into the performance levels of the various P/M grades. The large ovals encompass expected properties over a wide range of densities and processing conditions.

OBJECTIVE COMPARISON OF P/M TO CAST IRON – A method of quantitatively comparing materials was developed in 1970 and refined in 1974 [9]. This method utilizes a combination of tensile strength and elongation to calculate a value known as the Quality Index (QI). The QI is equivalent to the square of the ultimate tensile strength (in 10^3 psi) of a material multiplied by its elongation divided by 1000. A larger QI value indicates a more desirable combination of properties. Nodular iron grades with strengths over 550 MPa have QI values between 29 and 38. Additionally, the minimum QI value for GM 84M is 20. The QI of select materials from Table VI and VII are calculated to be 9 - 28 (Grade 2), 22 - 42 (Grade 4), 13 - 33 (Grade MDA), 26 - 42 (Grade MDB), and 43 - 79 (Grade MDC). Although QI comparisons alone are not sufficient to ensure comparable performance, such analyses can serve as objective tools to be utilized in conjunction with application specifications and interactions with design engineers.

TABLE VI: Mechanical Properties of Select Material Grades Sintered at 1120 °C and Tempered at 190 °C

Grade	Density (g/cm³)	UTS (MPa / psi)	Yield (MPa / psi)	Elong. (%)
2	6.95	625 / 91,000	515 / 74,000	1.1
	7.20	800 / 115,000	560 / 81,000	2.1
4	7.01	785 / 114,000	540 / 78,000	1.7
	7.28	925 / 135,000	595 / 86,000	2.3
DH-1	6.79	525 / 76,000	490 / 71,000	0.7
	7.16	745 / 108,000	600 / 87,000	1.4
HP-1	6.94	715 / 104,000	500 / 72,000	1.2
	7.27	950 / 138,000	595 / 86,000	1.8
GM 84M	–	690 / 100,000 Min	550 / 80,000 Min	2 Min

TABLE VII: Properties of Silicon-Containing Grades Sintered at 1260 °C / Tempered at 190 °C

Grade	Density (g/cm³)	UTS (MPa / psi)	Yield (MPa / psi)	Elong. (%)
MDA	6.66	490 / 71,000	325 / 47,000	2.6
	7.04	650 / 94,000	400 / 58,000	3.8
MDB	6.80	675 / 98,000	505 / 73,000	1.8
	7.13	875 / 127,000	620 / 90,000	2.6
MDC	6.83	1045 / 151,000	765 / 111,000	1.9
	7.13	1250 / 181,000	825 / 119,000	2.4
8002* Nodular	–	690 / 100,000 Min	550 / 80,000 Min	2 Min

*Martensitic grade requiring a minimum of 90% martensite with typical hardnesses of 24-32 HRC.

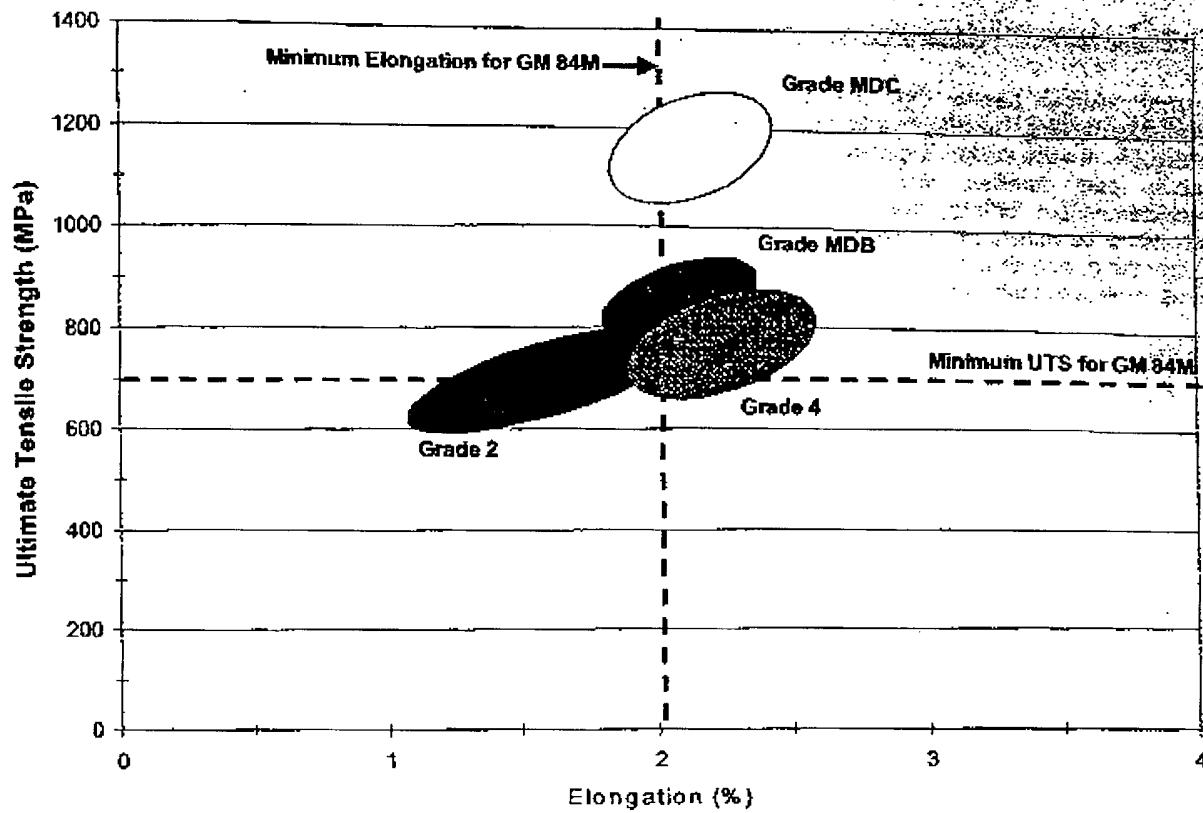


FIGURE 2: Strength and Elongation Requirements of GM 84M Compared with Properties of Several P/M Grades

POTENTIAL AUTOMOTIVE APPLICATIONS

The sheer number of potential conversion targets for P/M precludes a comprehensive listing. However, as many of the cast irons presented herein are referred to using GM specifications, it seems fitting to examine specific GM systems / components for conversion [2,3]:

- > Hydra-matic 4T80-E Transaxle
 - Input Carrier and Forward Sprag Clutch Assemblies
 - Internal Ring Gear (GM 84M)
 - Forward Clutch Support Assembly
 - Parking Lock Gear (GM 84M)
 - Final Drive Internal Ring Gear (GM 84M)
- > Hydra-matic 4T65-E Transaxle
 - Reaction Carrier Assembly (GM 84M)
 - Parking Gear (GM 84M)
- > Hydra-matic 4T40-E Transaxle
 - Final Drive Internal Ring Gear (GM 84M)
 - Input Carrier Assembly
 - Input and Reaction Internal Ring Gear (GM 84M)

- > Hydra-matic 4L80-E Transmission
 - Direct Clutch Driving Hub (Nodular Iron)
 - Forward Clutch Driven Hub (Gray Iron)
 - Overdrive Carrier Assembly
 - Overdrive Carrier (GM 84M)
- > Hydra-matic 4L60-E Transmission
 - Input Carrier Assembly (Nodular Iron)
 - Input Internal Ring Gear (GM 84M)
 - Internal Reaction Gear Support (Gray Iron)
 - Reaction Carrier Assembly (GM 84M)
- > Hydra-matic 4L30-E Transmission
 - Ring Gear (GM 84M)
 - Overdrive Carrier Assembly
 - Overdrive Carrier (GM 84M)

ADDITIONAL CONSIDERATIONS

There are three important points to be made at this time.

- It goes without saying that the conversion of automotive castings to P/M invariably requires close interaction with the design engineers assigned to the various part families and platforms. The specifications put forth by these engineers include such items as minimum fatigue thresholds, density requirements, and dimensional tolerances that could not be reviewed in this effort.
- The data shown for P/M grades are not the result of any special processing steps (other than some high temperature sintering). Hence, if pressed and sintered P/M falls short of meeting some application expectations, additional processing by techniques such as induction hardening, thread rolling, machining, brazing, etc. are certainly possible and, for the most part, well understood.
- Finally, the list of cast iron grades chosen for comparisons with P/M are not exhaustive. Hence, as can be seen in Table VIII, many lower performance castings are ripe for conversion to P/M [10]. It should be noted that every grade contained in the Table is closely matched by one or more of the P/M grades reviewed.

TABLE VIII: Property Requirements of Malleable Iron Castings for Automotive Applications per SAE J158

Cast Iron Grade	UTS (MPa / psi)	Mech. (MPa / psi)	Elong. (in. / in.)
M3210	345 / 50,000	225 / 32,000	10
M4504	450 / 65,000	310 / 45,000	4
M5003	515 / 75,000	345 / 50,000	3
M5503	515 / 75,000	380 / 55,000	3
M7002	620 / 90,000	485 / 70,000	2
M8501	725 / 105,000	585 / 85,000	1

CONCLUSIONS

Numerous opportunities exist to increase the total weight of P/M parts in the typical automobile by converting common cast iron grades. The P/M grades examined in this work have the capability to replace many cast irons, but close interaction with automotive design engineers is necessary. However, the P/M industry must bear in mind that, concurrently with these conversion attempts, automotive systems continue to increase their mechanical requirements in order to achieve higher powder densities. Although the road to conversion may be long and arduous, the paybacks for the automotive and P/M industries are immense.

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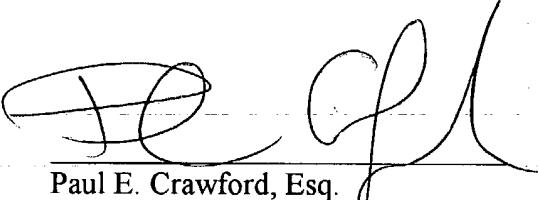
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